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A COMPARISON OF METHODS FOR CALCULATING THE LOUDNESS LEVEL

E. Zwicker

1. Introduction /278*

In recent years it has become more and more well known that a frequency analysis of a sound is necessary if a useful statement is to be obtained about its loudness. If an employer wishes to calculate the loudness of a sound analytically, he has not one but three different methods of loudness calculation available. But it has been shown that there are differences between the results of the different methods for calculating loudness. This situation should not be surprising because the methods are fundamentally different. It leads to an important problem for the employer. Actually, there are two problems, and the two should be strictly separated from each other.

The first problem is: How great are the differences in the loudnesses calculated by the different methods, given the same spectra and levels as the basic input data for the method? Although only calculation and evaluation work is needed to answer this question, the answer has not yet been pursued systematically. In the following contribution, we shall deliberately not provide a complete explanation. Rather, we shall only study the spectral types in which the greatest differences between the various methods are to be expected, and how large these can be. This is because the computation cost for even this moderate answer is quite

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* Numbers in the margin indicate pagination in the original foreign text.

considerable, as levels, bandwidths, and the shape of the level diagram must be changed.

The second problem is: What loudness computation method most nearly approaches the actual preceived loudness, and how great are the differences between the calculated and perceived loudness? It is considerably more difficult to answer this second / 279 problem than the first one. Very many experimental subjects and an overwhelming expenditure of time would be necessary to answer this question, even if it were done only for the sounds which occur often in practice. Not only for this reason, the contribution provided here to the clarification of this second question can only be relatively slight. Rather, the author is of the opinion that these measurements should be performed by impartial persons who have not themselves participated directly in the development of loudness calculation methods. The investigations begun by Lübcke and Mittag [1] are in part a step in this direction. Nevertheless, some subjective comparisons were done, but only on those sounds for which the deviation between the calculated loudnesses appeared particularly clearly.

The first question is very important for standardization, because the various loudness calculation methods should yield results as nearly identical as possible. That the results still deviate from each other is deplorable for the moment. But, on the other hand, this situation conceals in itself the hope that the calculation methods will be improved step by step so that finally a very good approximation to the perceived loudness is obtained.

The author would like to insert a request here: The results reported in the following should not be used so that the "producer" of sound fastens onto that calculation method giving the smallest value with the particular spectrum present and, on the other hand, the "consumer" of sound should not feel attracted to the method giving the greatest value!

2. Methods Used

Three methods for calculating the loudness are to be compared with each other: the method of Niese [2], which comes from the A-rated sound pressure level; the method of Stevens [3], in which the loudness is calculated with a loudness index; and the method of the author [4], which comes from the specific loudness and the frequency group.

For both first methods, we can start from third levels as well as from octave levels. Third levels are a prerequisite for the last method. For uniformity, third level values were established as input data for all three methods. The method of Niese was first established for the plane sound field, while the method of Stevens applies only for the diffuse sound field. To be sure, the deviations arising from the sound field shape are not too great. They are 3 dB at 1000 Hz, and are less than ± 3 dB in the entire remaining frequency range up to 6 kHz. A deviation as great as 5 dB is reached only at very high frequencies above 8 kHz. In general, the difference due to the sound field shape will be only 1 or 2 dB for broad-band sounds. Where detectable differences between the results for the diffuse field and the results for the free field appear in the author's method, both values are given for this calculation method.

3. The Parameters of the Sound Used

The calculations were performed for sound pressure values of the sound of (30 dB), (40 dB), 60 dB, 80 dB and 100 dB. The bandwidths were used as other parameters. Here third band noises (these appear in the calculation of the same loudnesses as individual tones), octave noises, two-octave noises and broad-band noises were applied. The following parameters were chosen as center frequencies: (63 Hz), (125 Hz), 250 Hz, (500 Hz), 1 kHz, (2 kHz), 4 kHz (8 kHz). The parameter values given in parentheses are not presented additionally in the subsequent Figures. They also contain no particularly outstanding results. As a final parameter, but not an unimportant one, as will be seen below, the form of the third level diagram was changed. The slope of the curve of the sound intensity density level was chosen as a simple characteristic for the shape of the spectrum, if it is plotted versus a logarithmic frequency scale. For white noise, this slope is zero by definition. Aside from this value, slopes, α, of +1, -1, -2 and -4 dB per increase of frequency by one third were used for the calculation.

4. Results of the Loudness Calculations

The values calculated by the three methods for noise one or two octaves wide is shown in Figure 1a to f. The difference ΔL between the calculated loudness and the sound pressure level of the noise is plotted as the ordinate. The rise, α, of the sound intensity density level which occurs on increasing the frequency by a third is used as the ordinate. Of the results, those for the center frequencies of 250 Hz, 1 kHz and 4 kHz were selected. In the individual partial figures the total sound levels are held constant. They are 60 dB, 80 dB and 100 dB. The selected center frequencies with the three level values give a clear survey of the differences between the three calculation methods. The results / 280
according to the calculation method of Niese are marked with N. Those from the method of Stevens are marked with S. The values calculated by the author's method are marked with Z if the results obtained for the diffuse sound field and those for the plane field differ by less than 1 phon_G. In other cases, they are marked separately with D and F.

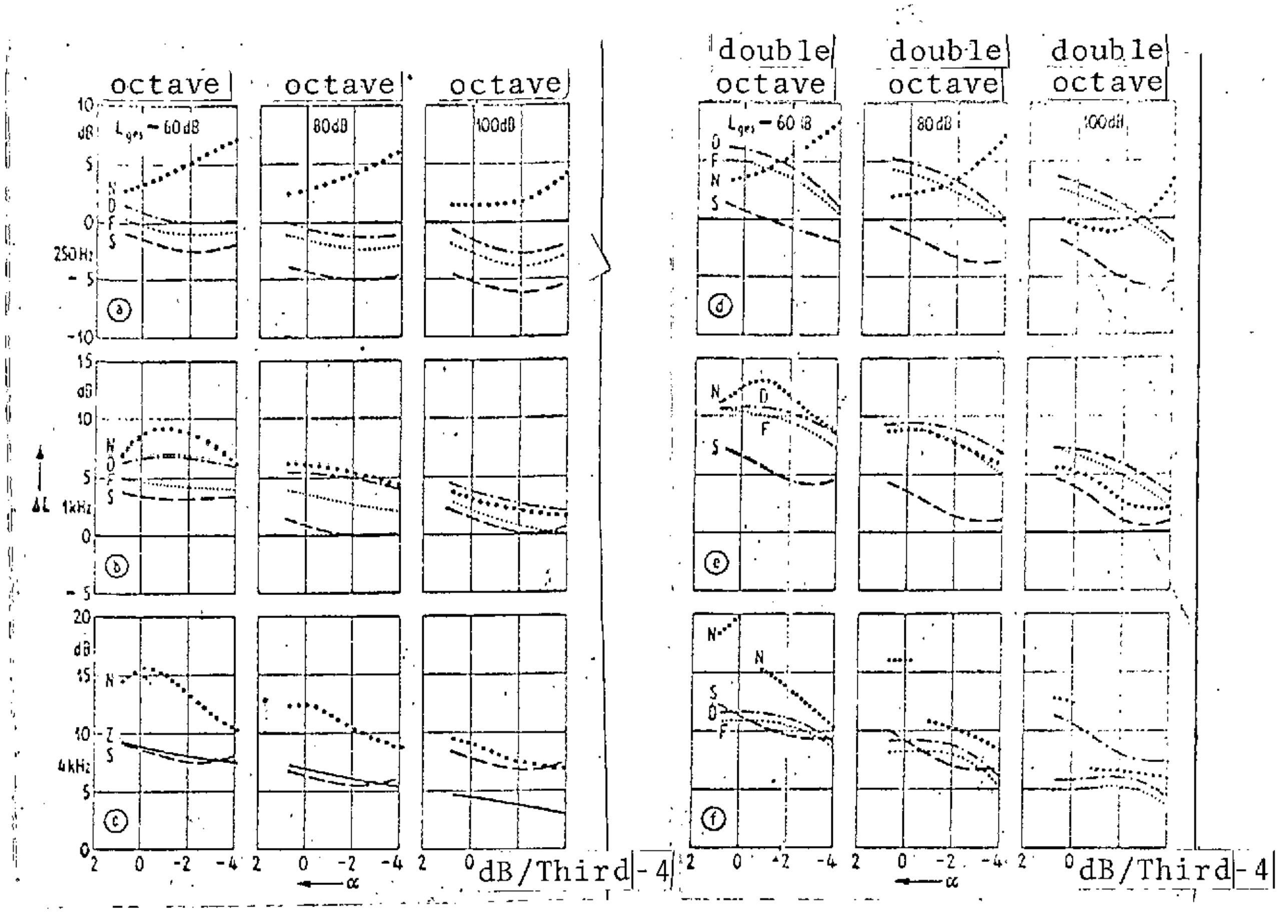

Figure 1. Calculated loudness value of octave-wide sounds (left part) and of two-octave-wide sounds (right part) for center frequencies of 250 Hz (top), 1000 Hz (center) and 4000 Hz (bottom). The value plotted is the difference ΔL between the calculated loudness (level of the equally loud 1 kHz tone) and the total sound pressure level as a function of the slope, α, with which the sound intensity density level rises per third with increasing frequency. The total sound pressure levels are always constant and shown as parameters. The results calculated by the method of Niese are plotted as circles and marked with N. Those calculated by the method of Stevens are shown as dashes and marked S; those by the author's method are plotted as solid lines and marked with Z. If the calculations for diffuse (dot-dash) and for free (dotted) sound fields give different values, they are marked with D and F.

In general it can be said that no such uniform statement can be made for octaves and double octaves, that the value of a certain method would always be above or below the values of the other method. For octave-wide sounds the results from the method of Niese are usually above the results of both the other methods, while the results from the method of Stevens are usually below the results of both the other methods. This effect becomes obliterated for double octaves because here a considerably stronger dependence on the spectrum shape appears. The irregularity in the dotted curves which occurs with double octaves at 4 kHz center frequency is therefore, related to the fact that this center frequency, at which the greatest A-rated third level appears, plays a decisive part in the method of Niese. As the form of the spectrum, and, correspondingly, the A-rating curve can change sharply corresponding to this center frequency, the plotted irregularity appears. The fact that the calculated loudnesses in phons for octave-wide sounds and center frequencies of 250 Hz differ only insignificantly from the total level in dB, i. e., at a level difference of some 0 dB, corresponds to the expected loudness values. The fact that they are a few dB above the 0 dB line at 1000 Hz center frequency and distinctly above at 4000 Hz likewise agrees with expectations for octave-wide sounds. With double octaves, aside /281 from the region of irregularity mentioned above, it is still striking that the slope of the curves as a function of the slope of the spectrum, for the band center frequency of 250 Hz has a different character for the different methods. While the curves according to Niese show a rising tendency toward higher frequencies with steadily steeper fall-off of the spectrum, the curves calculated by the other two methods fall off evenly.

For octaves and double octaves we can make the general statement from the comparison that the results from the three calculation methods differ very little in part, but in part they also differ as much as 10 dB, corresponding to 10 phons.

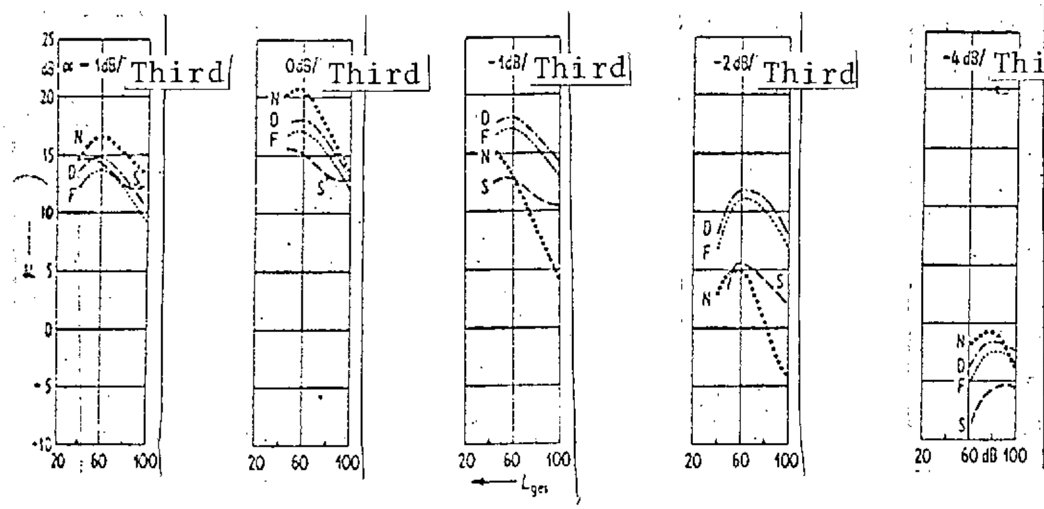

Figure 2. Calculated loudnesses of wide-band noises. The value plotted is the difference, ΔL, between the calculated loudness (level of the equally loud 1 kHz tone) and the total sound pressure level as a function of the latter. The parameter is the slope, α, of the intensity density level. Designations for the calculation methods used are as in Figure 1.

There is no method, however, which always produces values which are too large or too small. The deviations are not methodical.

The calculation results are presented in Figure 2 for broad-band noises with bandwidths of 45 Hz to 16 kHz. Again, the level difference between the calculated loudness and the total sound pressure level is plotted as the ordinate. The abscissa and parameter are interchanged, however, in comparison to Figure 1. In Figure 2 the total sound pressure level is chosen as the abscissa, while the slope of the spectrum changes from one part of the figure to another. The designation of the values calculated by the various methods is the same as in Figure 1.

For broad-band noises, we can speak of a methodical deviation of the values calculated with the various methods even less than in Figure 1. Which method gives the largest or smallest values does not depend only on the level, but also very strongly on the slope of the spectrum. For a noise having a sound intensity density level which rises with the frequency at 1 dB per third, the values from the Niese method of calculation are above those from both the other methods, quite similar to the results for a slope of 0 dB per third (which corresponds to white noise). For a slope of -1 dB per third in the spectrum, that is, for a noise with which the third levels remain constant with the frequency because the absolute bandwidth of the third increases with the frequency, the sequence is reversed. The author's method gives the highest values, while the methods of Stevens and of Niese give considerably lower values, especially at high levels. This effect is expressed even more strongly at a slope of -2 dB per third for broad-band noise, while a reversal occurs again at a very sharp slope of -4 dB per third. A comparison between the method of Stevens and the author's method shows that both methods give similar values for rising or horizontal spectra. In contrast, with a falling spectrum there are differences so that the results by the method of Stevens are below those from the author's method.

The deviations between the values calculated by the different methods differ by at most 5 dB for the rising and horizontal spectra, and for the sharply dropping spectrum. For the slowly falling spectrum, however, deviations of up to 10 dB occur. It is regrettable that such severe deviations occur in just this region, because a large number of everyday noises such as traffic noise, domestic noise and the like have spectra with considerable portions at low frequencies but which show decreasing tendencies at higher frequencies.

5. Subjective Loudness Comparisons

Both narrow-band and wide-band sounds were selected for the loudness comparison measurements. The narrow-band sounds were sine tones of 250 Hz, 4 kHz and 8 kHz as well as a narrow-band noise with the center frequency 1 kHz and the band width of 140 Hz (about one frequency group) with extremely steeply damped /282 edges. These narrow-band noises were selected so as to obtain measurements from the subjects participating which would be comparable to those published by Robinson as curves of equal loudness, and which are accepted as the international standard [5]. The wide-band noises were determined according to the greatest deviations appearing in Figures 1 or 2. Octave-wide noises were selected according to Figure 1a at a center frequency of 250 Hz, a level of 80 dB and a slope of -4 dB per third for the sound intensity density level. For the double-octave, a center frequency of 1000 Hz was chosen from Figure 1e, with a drop of -3 dB per third for the sound intensity density level. As the deviations are present at 60 dB and at 80 dB, a level of 70 dB was used as an intermediate level. From the presentation in Figure 2, a wide-band noise was selected with a sound pressure level of 70 dB and a sound intensity density level slope of -2 dB per third. The ideal third level diagram used for the calculation in Figures 1 and 2 could not be realized exactly in the presentation with a dynamic loudspeaker in a nonresonant room. The actual third level diagram of the sounds used for the loudness comparison measurements are shown in Figure 3.

The method of swinging compensation was used as the measuring method. Twelve subjects matched the 1000 Hz tone to the sound to be measured once, and then matched the sound measured to the 1000 Hz tone. The measurements were done in a nonresonant room in a plane sound field. The twelve subjects had ages between 22 and 27 years.

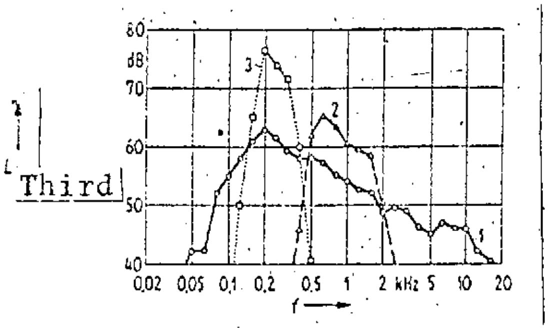

Figure 3. Third level diagram for the noise segments used for the subjective measurements:
Curve 1: broad-band noise
Curve 2: two-ocatave-wide noise
Curve 3: octave-wide noise

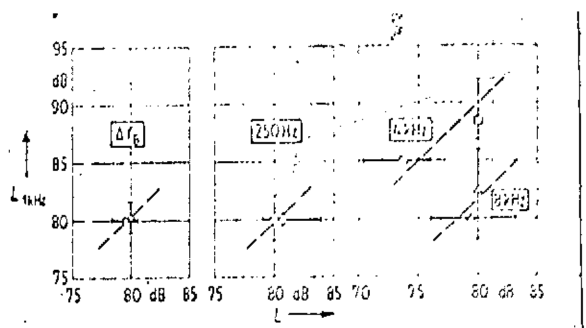

Figure 4. Mean variations and central values of the loudness comparison measurements with narrow-band noises. The plotted value is the level, $L_{1\ kHz}$ of the equally loud 1000 Hz tone versus the level, L, of the tones of 250 Hz, 4000 Hz and 8000 Hz or of the narrow-band noise about 1000 Hz. The interpolated loudnesses are plotted with dashed lines.

The results of the loudness comparisons for narrow-band noises are shown in Figure 4. It appears that a narrow-band noise of about 1000 Hz with a width less than the frequency group and a sound pressure level of 80 dB is just as loud as a 1000 Hz tone with the sound pressure level of 80 dB. The mean variation for this measurement is unusually small, so that it can be said with great certainty that narrow-band noises and sinusoidal tones are in fact equally loud if only their level is equally great, and the narrow-band noise has a bandwidth smaller than the frequency group. It must, to be sure, be assumed that the filter used has very sharp damping edges.

Figure 4 also shows the measurements for the 250 Hz tone, the 4 kHz tone and the 8 kHz tone. While a 250 Hz tone with a sound pressure level of 80 dB was set equally loud as an 80 dB 1 kHz tone by the test subjects, this equality of sound pressure level and loudness is not present with the 4 kHz tone. The interpolated loudness [6], which is plotted with dashed lines in Figure 4, is, for the 80 dB 4 kHz tone, 90 dB of the 1 kHz tone; that is, 90 phon. The measurements for the 8 kHz tone are shown in the right part of Figure 4. The interpolated loudness shows that an 80 dB 8 kHz tone has a loudness of 81.5 phon.

The measurements from the twelve subjects can be compared with the curves of equal loudness for sine tones published by Robinson. His results, along with those values obtained from the loudness calculation methods, are compared with the subjective measurements in Table I. The calculation method of Stevens is valid only for a diffuse sound field and should not be applied for single sine tones. The values calculated by this method are presented only for completeness. Comparison of the values given in Table I shows that the deviation is no more than ± 3 phon between the subjective measurements and between the calculated values and the measured values at 250 Hz and 4 kHz. In the /283

Table I. CALCULATED AND MEASURED LOUDNESSES

Calculated loudness according to	Sine tone		
	80 dB 250 Hz	80 dB 4 kHz	80 dB 8 kHz
Niese	70.5 phon_{N}	80 phon_{N}	80 phon_{N}
Zwicker free	78 phon_{GF}	84 phon_{GF}	74.5 phon_{GF}
diffuse	78.5 phon_{GD}	83 phon_{GD}	78.5 phon_{GD}
Stevens	75 phon_{TD}	80 phon_{TD}	80.5 phon_{TD}
Measured free-field loudness			
Robinson	83 phon	90 phon	74 phon
Our value	80 phon	90 phon	81.5 phon
Measured audibility threshold, free-field			
Robinson	+ 14 dB	− 4.5 dB	+ 11.5 dB
Our value	+ 11 dB	− 4 dB	+ 15 dB

author's opinion, this accuracy will not be reduced even with greater care, and it must be considered as corresponding satisfactorily to the present state of the measuring technology. The deviations at 8 kHz are very large both between the subjective measurements and in particular, between the calculated values. In this frequency range not only the psychological measuring method, i. e., the estimation of the subjective sensation, but also the objective measurement presents significant difficulties, as $\lambda/4$ is already of the order of magnitude of 1 cm or less. The

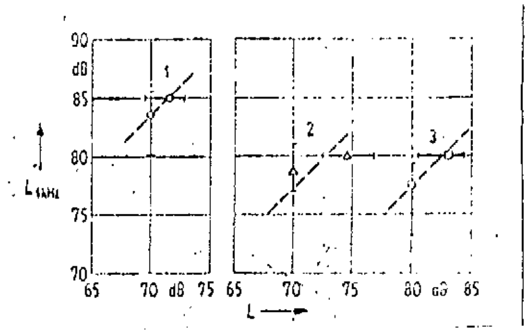

Figure 5. Mean variations and central values of the loudness comparisons for noises 1, 2, and 3 with the third-level diagrams shown in Figure 3. The plotted value is the level, $L_{1\ kHz}$ of the equally loud 1000 Hz tone versus the level, L, of the noise. The interpolated loudnesses are plotted with dashes.

Table II. CALCULATED AND MEASURED LOUDNESSES

Calculated loudness according to	Noise 1	Noise 2	Noise 3
Niese	77 $phon_N$	79 $phon_N$	87.5 $phon_N$
Zwicker			
free	83.5 $phon_{GF}$	77.5 $phon_{GF}$	78.5 $phon_{GF}$
diffuse	84.5 $phon_{GD}$	78.5 $phon_{GD}$	79 $phon_{GD}$
Stevens	78.5 $phon_{TD}$	74 $phon_{TD}$	76 $phon_{TD}$
Measured loudness			
Free-field	83.5 phon	77 phon	77.5 phon

fact that the calm audibility thresholds agree accurately to $\pm$ 3 dB shows that the group of subjects who participated in the measurements corresponded to the requirements.

Results of measurements of broad-band noises are shown in Figure 5. The level of the equally loud 1 kHz tone is again plotted versus the level of the noise. The measurements showed that the broad-band noise 1 has a loudness of 83.5 phon at a level of 70 dB; the two-octave-wide noise 2 has a loudness of 77 phon at 70 dB; and the octave-wide noise 3 at 250 Hz has a loudness of 77.5 phon at 80 dB sound pressure.

The loudness values calculated from the third-level diagrams (Figure 3) are shown in Table II for the broad-band noises. In part, deviations of $\pm$ 3 phon between the subjective measurements and the calculated values are exceeded. While the value calculated by the method of Niese is considerably below the subjective measurement in particular for noise 1, just the opposite is true for the value calculated according to Niese for noise 3. For noise 2, in contrast, the calculated values are near the subjectively measured values. The deviation of $\pm$ 3 phon is not exceeded. At this point, we should mention once more that the method of Stevens is inherently valid only for the diffuse sound field. The difference between the values calculated for the diffuse sound field and the plane sound field by the author's method may indicate the deviations to be expected.

6. Discussion

As mentioned initially, the present investigation resulted more from the wish to open a discussion on this subject. As the results presented have neither answered completely all the questions related to the subject, nor solved the problems arising, and /284
because the author cannot be considered entirely unbiased in this

relation, he may be allowed to limit the discussion considerably at this point and replace it by a brief summary of the results.

The three loudness calculation methods studied give results which, to a large extent, do not differ from each other by more than ± 3 dB, even for different sounds. In individual cases, however, deviations are as great as 10 dB. The deviations are not methodical, but depend very strongly on the sound pressure level and on the form of the third level diagram of the sound to be evaluated. A comparison with subjective measurements shows that the loudness values calculated by the method of Stevens are below the measured values, while those calculated by the method of Niese are partly below and partly considerably above the subjective measurements.

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16. Abstract

The methods at present in use for calculating the loudness level yield differing results for the same sound spectrum. According to three methods [2, 3, 4], the loudness level is calculated as a function of sound pressure level, band width, center frequency and slope of the third-octave level diagram, and the results are compared. The differences vary between 0 dB and 10 dB, depending on the nature of the sound. The divergences are not methodical. To gain a criterion for the actual (the subjectively perceived) loudness, measurements were made with 12 persons for several sounds which presented especially large differences among the calculated values.

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